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MESUREMENT OF TOP QUARK PROPERTIES AT THE TEVATRON

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We highlight the most recent top quark properties measurements performed at the Tevatron collider by the CDF and DØ experiments. The data samples used for the analyses discussed correspond to an integrated luminosity varying from 360 pb^{-1} to 760 pb^{-1}.

1 Introduction

Since its discovery at Fermilab in 1995 [1], the top quark has been intensively studied but most of its properties are still poorly understood due to its small production cross section and the resulting statistically limited data samples. The constraints currently set by precision electroweak measurements leave plenty of room for exotic behaviors, and direct measurements of top quark properties are necessary to explore physics beyond the Standard Model. This paper summarizes the most recent measurements of fundamental top quark properties performed by the CDF and DØ collaborations at the Tevatron. It covers the first direct measurement of the top quark lifetime and electric charge, the search for exotic production modes through heavy resonance decays, the search for a 4^{th} generation of quarks, and the measurement of the W boson helicity.

At the Tevatron, the Standard Model (SM) predicts that the top quark is produced predominantly in pairs with a cross section of about 7 pb and to decay almost 100% of the time into a W boson and a b quark [2]. To achieve precision measurements of top quark properties, a large and pure sample of top quarks is required. Therefore, only $t\bar{t}$ events where at least one of the W bosons decays leptonically to an electron or a muon are considered. The lepton+jets and dileptons events, containing at least one isolated high P_T lepton, two high P_T b jets and a large missing transverse energy ($\not\!\!E_T$) due to the escaping neutrinos in the final state represent 30% of top quark events and have a relatively low background contamination. To increase the purity of the data sample, most of the analyses require at least one jet to be identified with a secondary vertex found inside the jet, which is a characteristic of the decay of long-lived particles such as B or D mesons.

2 Top quark lifetime

Under the SM assumptions and in the abscence of extra lepton generations [3] the top quark lifetime is constrained to be less that $10^{-24}s$, translating into a time-of-flight $c\tau < 3\times10^{-10}$ μm. The first direct measurement of the top quark lifetime was performed by the CDF experiment with 318 pb^{-1} of data. This measurement is designed to confirm the identity of the top quark candidates and to detect unexpected production modes through new long-lived exotic particles.

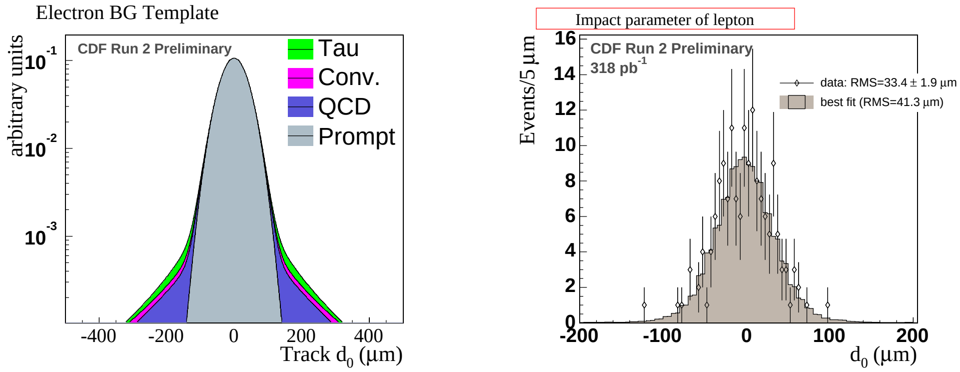

Figure 1: Left : Lepton impact parameter (d_0) distributions of the background in the e+jets channel. Right: Comparison of the lepton d_0 distribution in the data (points) with the best fitted Monte-Carlo template (histogram). The histogram includes the signal $c\tau = 0$ μm and the background contributions and is smeared to account for the detector resolution.

The lifetime information is extracted by measuring the distance between the initial collision point and the W boson decay vertex, given by the lepton impact parameter d_0. The lepton impact parameter distributions are built by combining the simulated top quark signal and backgrounds normalized to the expected sample composition. The background consists of prompt leptons coming from $W(\rightarrow e, \mu)$+jets events, leptonic decays of heavy flavor jets from QCD multi-jets events, photon conversions and $W(\rightarrow \tau \rightarrow e, \mu)$+jets. The lepton impact parameter distributions are shown in Figure 1 for each background component. The impact parameter templates are generated for a top quark lifetime varying between $0\ \mu m < c\tau < 500\ \mu m$, and smeared to take into account the detector resolution. The lepton d_0 distribution in data is then fitted using a maximum likelihood fit method and is consistent with the SM prediction $c\tau = 0\ \mu m$. Figure 1 shows the data superimposed to the best fitted template. A limit on the top quark lifetime $c\tau < 50\ \mu m$ can be derived at 95% confidence level.

3 Top quark charge

In the SM, the top quark has an electric charge of $+\frac{2}{3}e$. However, exotic models [4] involving a 4^{th} generation of heavy quarks suggest that the top quark candidates found at the Tevatron may be mistaken with an exotic heavy quark, very similar to the top quark but with an electric charge of $-\frac{4}{3}e$. The first direct measurement of the top quark charge has been performed by the DØ experiment with 370 pb^{-1} of data. The top (anti-top) quark charge is defined as the charge of the lepton plus (minus) the charge of the associated b jet. The first step for this measurement requires the reconstruction of top quark pair candidates with a kinematic fit in order to find the correct lepton/b jet pairing. The lepton charge is determined using the curvature of the track. The b jet charge is determined with a *jet charge algorithm* using all tracks with $P_T >$ 0.5 GeV/c found in the jet to calculate a P_T weighted mean charge. The *jet charge* distribution is calibrated using an independant data sample enriched with semi-leptonic b decays. In the calibration sample, the charge of the b jets is derived from the lepton charge, accounting for c jet contamination and B oscillation corrections. Figure 2 compares the charge distribution of the top quark candidates reconstructed in data with the $+\frac{2}{3}e$ and $-\frac{4}{3}e$ charge hypotheses. A likelihood ratio defined as

$$\Lambda = \frac{\Pi_i p^{sm}(q_i)}{\Pi_i p^{ex}(q_i)}$$

is then computed to determine the most probable model. The numerator measures the probability p^{sm} for a charge distribution to agree with the SM hypothesis, while the denominator measures the probability p^{ex} for the charge distribution to agree with the exotic quark model. The value of the likelihood ratio measured in data is compared to the Λ^{SM} and Λ^{ex} distributions, derived by performing ensemble tests using the SM or the exotic quark charge hypothesis for the signal respectively. For the exotic heavy quark hypothesis, only 6% of the pseudo-experiments gives a higher Λ ratio than the one measured in data (Figure 2). Therefore, the existence of heavy quarks with a charge $-\frac{4}{3}e$ can be excluded at 94% confidence level.

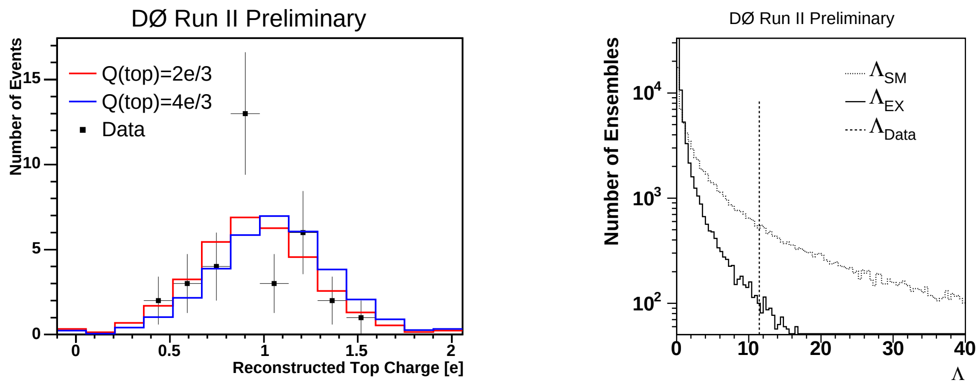

Figure 2: Left : Comparison of the charge distribution of the top quark candidates reconstructed in data (points) with the $+\frac{2}{3}e$ (red line) and $-\frac{4}{3}e$ (blue line) models. Right : Likelihood ratio distributions Λ^{SM} for the $+\frac{2}{3}e$ top quark charge hypothesis (dotted line) and Λ^{ex} for the $-\frac{4}{3}e$ exotic quark charge hypothesis (solid line).

4 Search for $t\bar{t}$ resonant production

This search was performed by both CDF and DØ collaborations and is dedicated to testing the hypothesis of top quark pair-production through the decay of a new heavy gauge boson. In such a case, the measured production cross section would be higher than predicted by the SM and a resonance would appear in the $t\bar{t}$ invariant mass distribution. The search is model-dependant [5], and restricts the resonance mass M_X to the range [350 - 1000] GeV/c^2 under the assumption of a width $\Gamma_X = 0.012 M_X$. The jet/lepton assignement the most consistent with the top decay hypothesis is chosen and the invariant mass of the reconstructed top quark pair candidates found in data is compared to the background and top quark distributions, normalized to the SM expectation. Since no excess is observed in data, both experiments can exclude a leptophobic Z' boson with a mass $M_x < 680$ GeV/c^2 at 95% confidence level for DØ with 370 pb^{-1} of data and $M_x < 725$ GeV/c^2 at 95% confidence level for CDF with 682 pb^{-1} of data.

5 Search for new heavy quarks t'

This search was performed by the CDF collaboration with 760 pb^{-1} of data under the assumption that the exotic quark is produced in pairs, decays promptly into a W boson and a b jet, and has a higher mass than the SM top quark [6]. In order to distinguish the t' signal from the top quark, a 2-dimensional function using the reconstructed mass of the heavy quark candidates and the total transverse energy in the event is built. The 2-dimensional distribution is then fitted with a binned likelihood method using a combination of templates for the t', $t\bar{t}$, W+jets and other SM backgrounds contributions. The W+jets production cross-section is a free parameter of the fit, while the $t\bar{t}$ and other backgrounds contributions are normalized to the SM expectation. Signal templates with $M_{t'}$ varying in the [175 - 400] GeV/c^2 range were considered, but no evidence of a t' signal was found. Therefore heavy quarks with a mass $M_{t'} <$ 258 GeV/c^2 can be excluded at 95% confidence level.

6 W boson helicity

The analysis presented here was done by the DØ collaboration and used 370 pb^{-1} of data. Assuming a massless bottom quark, the V-A structure of the SM weak interaction constrains the fraction of W bosons with right helicity (f_+) produced in $t \to Wb$ decay to be less than 3.6×10^{-4}. The fractions of W bosons with longitudinal (f_0) and left (f_-) helicities are expected to be 70% and 30% respectively. Experimentally, the W boson helicity is measured from the angle $cos\ \theta^*$ between the charged lepton and the top quark boost directions, measured in the W boson rest frame. Leptons coming from right-handed W boson are preferentially emitted along the top quark direction, leading to smaller $cos\ \theta^*$ values than for left-handed W bosons. A kinematic fit is used to reconstruct the top quark pairs and the W boson rest-frame. In dilepton events, the presence of two neutrinos leads to an underconstrained system and gives two possible angle measurements. Both combinations show discrimination between the V-A and V+A models and are used in the fit. Figure 3 compares the $cos\ \theta^*$ distribution in data with the simulated distributions for the pure V-A and pure V+A couplings hypothesis in lepton+jets and dilepton channels. The measured value of $cos\ \theta^*$ is extracted using a binned maximum likelihood fit for each channel. The combined result gives $f_+ = 0.06 \pm 0.08(stat) \pm 0.06(syst)$ and allows for the setting of an upper limit of $f_+ < 0.23$ at 95% confidence level.

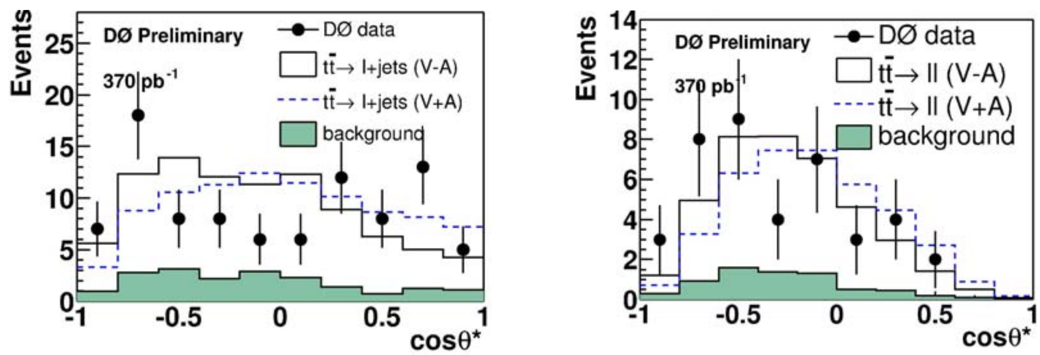

Figure 3: Comparison of the $cos\ \theta^*$ distribution in data (point) with the Monte-Carlo distributions expected for the pure V-A and pure V+A couplings hypotheses (histograms) in lepton+jets (left) and dilepton (right) channels.

7 Conclusion

The top properties measured so far are consistent within errors with SM predictions. The analyses are still statistically limited, but were intensively optimized and have already reached interesting precisions. The CDF and DØ collaborations have now more than 1 fb^{-1} of data recorded. These data are currently being analyzed. and more precise measurements are expected for the summer of 2006.

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